The HIF Transport Code FOCI

D.W. Hewett
Lawrence Livermore National Laboratory
Livermore, California 94550

R.O. Bangerter
Lawrence Berkeley Laboratory
Berkeley, California 94720

Abstract

A new HIF code, FOCI, combines the capabilities of several codes. 1) The x, y envelope equations are integrated in the axial direction. 2) An optimizer varies selected transport system parameters to make the envelope satisfy weighted constraints. 3) Transverse particle motion can be followed simultaneously. 4) The **E** field used for the particle advance is computed from from Poisson's equation using the local beam charge density as input. 5) Longitudinal velocity variations can be included in the particle description.

I. Introduction

Heavy Ion driven inertial confinement Fusion, or HIF, is a very promising area of energy research. Realizing the promise requires heavy ion accelerators capable of delivering adequate beams to the target. Much research is presently devoted to generating, accelerating, and manipulating such beams. Although the physics of alternating gradient transport and acceleration is a complex 3D process, much system design can be accomplished with a 2D "slice" model. Such 2D modeling (representing the beam as if it were infinitely long) grasps the features necessary to design many aspects of the final focusing system. We plan to employ this model, coupled with several other capabilities, in the new code FOCI that will be used in the design of the final focus section between the main accelerator and the target chamber.

II. Code Description

1) The first FOCI capability is the ability to integrate the transverse x, y envelope equations as the beam progresses in the axial direction z through a given quadrupole configuration. The basic envelope equations arise from the Lorentz force and Newtonian mechanics. The time dependence is converted to a z dependence assuming all particles have the same v_z. Using leapfrog finite differencing, we have

$$u_e^{n+1/2} = u_e^{n-1/2} + \Delta z\left[\frac{2P}{(x_e^n + y_e^n)} - K(z)x_e^n + \frac{\epsilon^2}{(x_e^n)^3}\right]$$

$$v_e^{n+1/2} = v_e^{n-1/2} + \Delta z\left[\frac{2P}{(x_e^n + y_e^n)} + K(z)y_e^n + \frac{\epsilon^2}{(y_e^n)^3}\right]$$

$$x_e^{n+1} = x_e^n + \Delta z u_e^{n+1/2}$$

$$y_e^{n+1} = y_e^n + \Delta z v_e^{n+1/2}$$

where the superscript n is the z step number and P is the perveance given by

$$P = \frac{eI_pZ^2}{2\pi\epsilon_0 p(\beta\gamma c)^2},$$

K is given by

$$K(z) = \frac{B_{quad}(z)}{a_{quad}(z)}\frac{Ze}{p},$$

and ϵ is the unnormalized emittance. The quantity $I_p = I_{electric}/Z$ is the particle current, the particle momentum $p = Am_n\gamma\beta c$, and $Z, A, e, m_n, c, \beta, \gamma$ are the particle charge state, mass number, electronic charge, mass per nucleon, speed of light, β and γ factors, respectively, in MKS units. B_{quad} is the amplitude of the quadrupole magnetic field strength evaluated at the aperture or pole-tip radius a_{quad}.

2) To facilitate design the results of the envelope integration may be fed into an optimizer. The envelope positions x_e and y_e and velocities u_e and v_e are used as input to an optimizer that automatically varies selected transport system parameters, such as length, a_{quad}, and B_{quad}, in an attempt to satisfy a prescribed set of weighted constraints. The formulation is a minimization of the function

$$F = \frac{1}{2}\Sigma w_i[a_i(x_j) - c_i]^2$$

where c_i is the value we desire for the i^{th} attribute $a_i(x_j)$ and w_i is the weight that determines how important this desire is relative to all others. We have made explicit the dependence of the i^{th} attribute on the independent lattice parameters x_j. Taking first and second derivatives with respect to the parameters x_j, we arrive at the linear system

$$\mathbf{A}\delta\mathbf{x} = -\mathbf{B}$$

where the elements of $\mathbf{A}$ and $\mathbf{B}$ are $\frac{\partial^2 F}{\partial x_j \partial x_k}$ and $\frac{\partial F}{\partial x_j}$, respectively, and the elements of the solution δx_j are approximate adjustments to be used for the next iteration.

0-7803-0135-8/91$01.00 ©IEEE

We approximate the matrix **A** by

$$A_{j,k} = \Sigma w_i \frac{\partial a_i}{\partial x_j} \frac{\partial a_i}{\partial x_k}.$$

The combination of an optimizer with the envelope integration allows simple, rapid design of a transport system that can, using final focus as an example, satisfy a constraint on the final focus spot size in concert with minimum drift length or aperture size that might be desirable for economic reasons.

3) In addition to these first two relatively standard code features, we have added the capability of integrating an ensemble of particles along with the envelope equations. As in Haber's SHIFTXY, arbitrary particle distributions may be initialized within the initial envelope. The x, y particle motion, after the same transformation to z dependence as the envelope equations, is then followed using PIC methods. The equations are

$$\begin{aligned} u^{n+1/2} &= u^{n-1/2} + \Delta z\left[f E_x(x^n, y^n) - K_p x^n\right] \\ v^{n+1/2} &= v^{n-1/2} + \Delta z\left[f E_y(x^n, y^n) + K_p y^n\right] \\ x^{n+1} &= x^n + \Delta z u^{n+1/2} \\ y^{n+1} &= y^n + \Delta z v^{n+1/2} \end{aligned}$$

where $K_p = K$. The particle force that arises from the beam space charge self-field and the contribution from the conducting wall is expressed in the terms containing the electric field components. The coefficient is

$$f = \frac{Ze}{\gamma A m_n \left[\beta\gamma c\right]^2}$$

and the electric field components are obtained from linear interpolation at the particle position.

4) The **E** field used to advance the particles is computed from a Poisson solution for ϕ using the charge density of these particles at the end of a step in z. This charge density is accumulated, using linear interpolation onto a Carteasian mesh, from the distribution of particles at their new positions x^{n+1}, y^{n+1}. The Poisson equation is also solved on this mesh. The Poisson method we use has provisions for arbitrarily shaped conducting pipes that may be specified along the axis correctly accounting not only for local nonuniformities in **E** but also for external conducting boundary conditions that provide image charge effects as the pipe radius varies with z. Thus far, we have used only circular pipe cross sections. In addition, the code will run only 1/2 or 1/4 of the cross section when beam symmetry allows effectively doubling or quadrupling the particle representation.

5) Longitudinal velocity variations can be included in the particle description by allowing the momentum for each particle $p \rightarrow p + \delta p$. The particle equations are easily modified by replacing K_p and f by

$$K_p \rightarrow \frac{K_p}{(1 + \frac{\delta p}{p})}$$

and

$$f \rightarrow \frac{f}{(1 + \frac{\delta p}{p})^2}.$$

The features described in 3), 4), and 5) allow accurate chromatic aberration evaluation in the presence of space charge as well as realistic (non KV) distribution functions for the beam representation. In the future we plan to use these features to consider more complex applied fields.

We have tested the code on the final focus system used in the HIBALL II study. We find good agreement on all three levels of description: the envelope, the K-V particle distribution, and the K-V distribution with $\delta p/p = 0.01$ solutions.

III. Acknowledgements

Work performed under the auspices of the United States Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.